7.2 A 2.6 inch VGA LCD with Optical Input Function using a 1-Transistor Active-Pixel Sensor

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The desire for smaller, lower-cost portable multimedia devices, along with recent advances in TFT technology, is driving the integration of advanced functionality onto LCD display substrates [1-3]. Historically, active matrix LCD (AMLCD) devices have utilized thin-film amorphous silicon transistors as pixel switches to enable larger, higher resolution displays than would otherwise be possible. More recently, the development of low-temperature polysilicon (LTPS) thin-film transistors (TFTs) has permitted the integration of display driver circuits onto the display glass substrate. Now, with the advent of advanced TFT processes, such as Sharp's continuous grain (CG) silicon technology, it is possible to integrate other functions onto the display glass substrate thereby adding value to the display and facilitating a significant evolution in the design of mobile devices.

In this paper we present a 2.6 inch VGA (640×480) AMLCD with an integrated optical input function that provides a 300dpi sensor output image at a 30Hz frame rate. A 1-transistor (1T) active-pixel sensor (APS) circuit is integrated within each display pixel to achieve a total aperture ratio of 40%. With this technology, functions such as touch/pen input and fingerprint scanning may be achieved within one ultra-thin low-cost display module.

The key enabling technology for this device is the CG-silicon TFT process. This proprietary process allows TFTs with higher performances than those of standard LTPS processes to be fabricated on the display glass substrate (see Fig 7.2.2). The image sensor's photosensor elements are thin-film lateral PIN-type photodiodes, formed on the glass substrate alongside the TFTs in the same CG-silicon process.

The lack of a substrate connection and low parasitic capacitance of the lateral photodiode structure provides additional degrees of freedom in circuit design not open to the conventional CMOS image sensor. For example, as will now be described, by using a combination of (1) reset through the photodiode and (2) row select via the integration capacitor, the need for the reset and row-select transistors of the standard 3T-APS pixel circuit is obviated. As shown in Fig. 7.2.3, the resulting 1T-APS pixel circuit comprises only the lateral PIN photodiode (PD), an integration capacitor (C_{INT}) and a source follower TFT (M1).

The operation of this 1T pixel circuit is described with reference to the circuit diagram of Fig. 7.2.3 and the waveforms shown in Fig. 7.2.4. At the start of the integration period, the voltage of the integration capacitor is reset to an initial value by temporarily pulsing the reset signal RST. When RST is brought high, the voltage of integrating node V_{INT} is reset to an initial reset potential of $V_{DDR} - V_F$ via the forward biased photodiode (where V_F is the diode forward voltage drop). Since the RST high potential is less than the threshold voltage of the source follower transistor M1, it remains off during the reset and subsequent integration periods. At the end of the reset period RST is brought low to a potential of V_{SSR} and the photocurrent of the now reverse biased photodiode is integrated on the integration capacitor.

When a row of pixels is sampled at the end of the integration period, the row select signal RWS is pulsed high and charge injection occurs across the integration capacitor. The integrating node is now raised above the threshold voltage of the source follower transistor M1 and the pixel source follower amplifier is now formed with the bias transistor M4 located at the end of the column. At the end of the pixel sample period, signal RWS is returned to a low potential and charge is removed from the integrating node by injection across the integration capacitor. The potential of the integrating node now drops below the threshold voltage of the source follower transistor M1, turning it off.

In order to maximize the display aperture ratio, the image sensor pixel circuit is integrated within the display pixel such that the matrix column lines are used both for writing the pixel display data and reading the sensor column data (see Fig. 7.2.5). The sensor pixel sample operation is performed during the display row blanking period so that no change to the display operation timing is required.

While the reduction in sensor pixel circuit size is the most obvious benefit of this 1T-APS architecture, there are a number of other advantages. Firstly, a reduced pixel sample time is possible due to the elimination of the parasitic on-resistance of the row-select transistor. Secondly, a lower operating voltage is possible since the pixel source-follower TFT gate voltage is decoupled from the supply voltages of the rest of the circuit. Finally, a higher dynamic range is possible as a result of the reduced voltage across the photodiode during the integration period.

The complete AMLCD panel block diagram is shown in Fig. 7.2.1. In addition to the pixel matrix, the circuitry integrated onto the display substrate includes display source and gate drivers, the sensor row driver and the sensor read-out circuits. The sensor row driver includes high-voltage level shifters to generate the special voltages required for the pixel circuit input signals. The sensor read-out circuit includes the pixel amplifier current source and sample circuit, column amplifier and chip amplifier as commonly found in standard CMOS imager ICs. The LCD controller (LCDC) IC contains an 8b ADC to convert the analog output from the image sensor circuits integrated on the LCD panel. Processing of the raw output image to generate, for example, touch input data may be performed in either the LCDC or the host device (mobile phone, PDA etc.).

This panel has been successfully fabricated and an example output image is shown in Fig. 7.2.6. For reference, an AMLCD panel containing a standard 3T-APS pixel circuit and an AMLCD panel with no sensor circuit were also fabricated. Compared to the 3T-APS panel, the 1T-APS panel had a 49% increase in aperture ratio, exhibited a 45% decrease in sensor pixel sampling time and an 80% increase in sensor dynamic range. Compared with the display only panel, the 1T-APS panel exhibited an aperture ratio reduction of only 18%. The resulting reduction in display brightness is therefore comparable with current resistive and capacitive touch input technologies, which require additional layers on top of the LCD panel.

The success of forming a high-resolution real-time image sensor within an AMLCD proves that our strategy of integrating added functions onto the display substrate is both feasible and realistic. Not only can existing applications, such as touch input, be integrated at a lower cost with no loss in performance, but additional applications, such as fingerprint identification, become possible. Underlining this strategy, we have demonstrated in this paper a new circuit technology that can revolutionize displays by turning them into true I/O devices.

References:
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[2] T. Nishibe et al., "Quite a New Approach for System-on-Glass Technology Based on Low-Temperature Polycrystalline Silicon," pp 359-362, *Proc. IDW*, 2003.
[3] K. Maeda et al., "The System-LCD with Monolithic Ambient-Light Sensor System," *Proc. SID*, May, 2005.

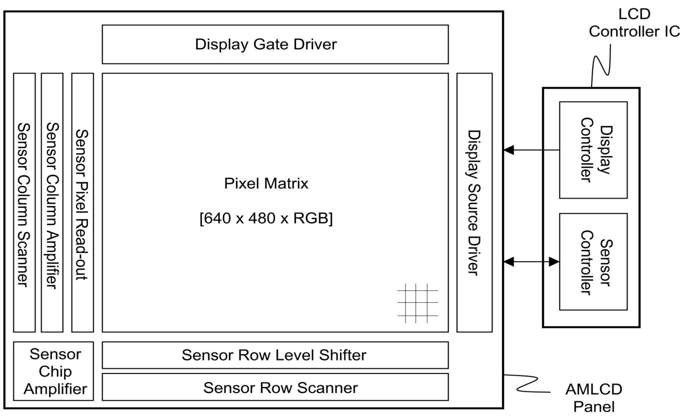

Figure 7.2.1: Panel block diagram.

Panel	Type	2.6 inch Transmissive
	Format	VGA (640 x 480)
	Pixel Size	84 x 84µm (300dpi)
	Aperture Ratio	40%
Display Circuit	Frame Rate	60Hz
	Driver Type	8-Phase Monolithic Analogue
	Colour	RGB
	Operating Voltage	V_{SS} = 0V, V_{DD} = 8V
Sensor Circuit	Frame Rate	30Hz
	Output Format	Analogue
	Colour	Greyscale
	Photosensor	Lateral P-I-N photodiode
	Pixel Architecture	1T APS
	Operating Voltage	V_{SS} = 0V, V_{DD} = 8V, V_{SSR} = -5V, V_{DDR} = 0V
TFT Characteristics	Process	CG-Silicon, 1.5µm
	Threshold Voltage	1.5V
	Mobility	300$cm^2V^{-1}s^{-1}$

Figure 7.2.2: Display specification table.

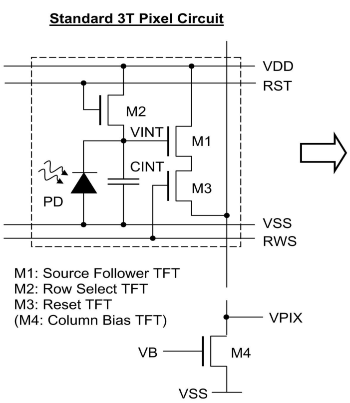

Figure 7.2.3: Comparison of 3T and 1T sensor pixel.

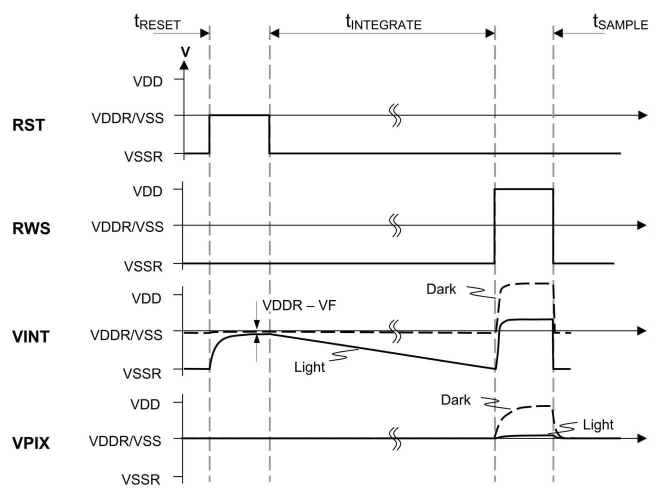

Figure 7.2.4: Pixel waveform diagram.

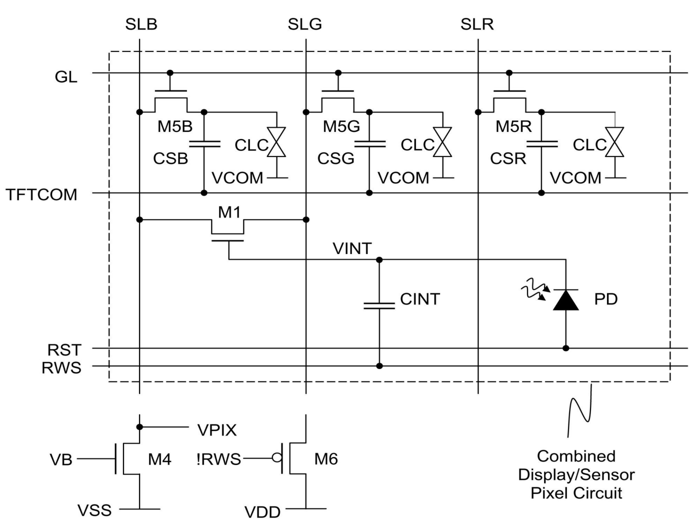

Figure 7.2.5: Combined display/sensor pixel circuit.

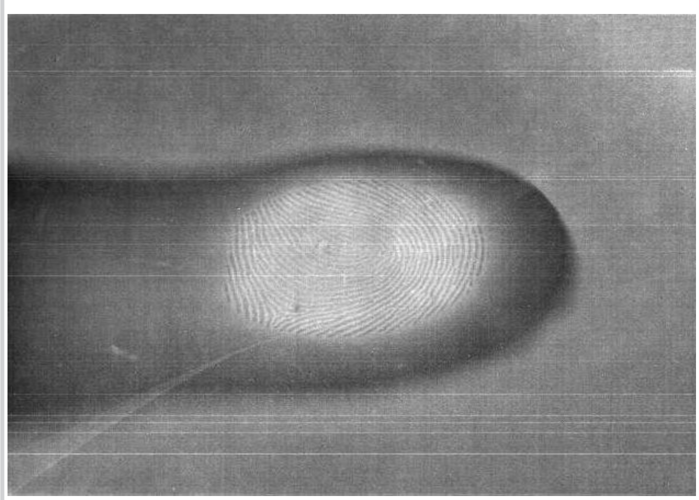

Figure 7.2.6: Sample captured image.

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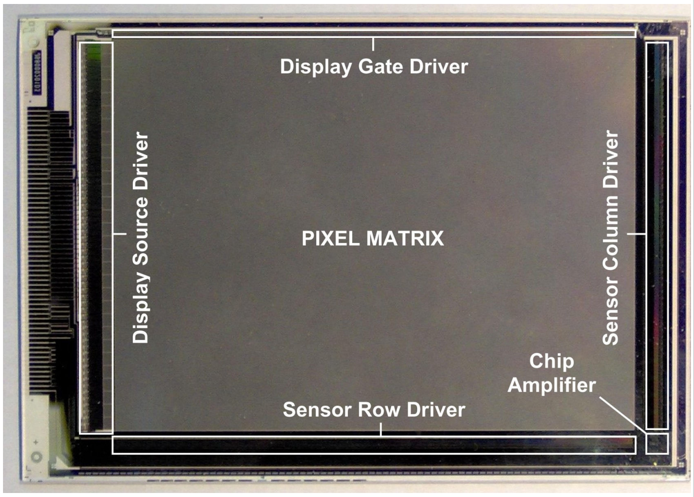

Figure 7.2.7: Photograph of display panel.

